

Spin polarization of electron current on the quantum well with exchange-splitted levels

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The backscattering process of injected electrons on exchange-splitted levels of quantum well (QW) in ferromagnetic metal / insulator / semiconductor heterostructure is studied. It is found that, if one of the exchange-splitted levels lies in the top region of the QW and the energy of injected electrons is close to the energy of localized electron on this level, the backward scattering becomes dependent on spins of injected electrons. Accumulation of backscattered electrons in the QW leads to considerable reduction of the current depended on its spin orientation. The spin polarization increases with growth of the applied electric field and the storage time of electrons in the QW. High values of the spin polarization can be achieved at room temperature. In this way, the QW with exchange-splitted levels in ferromagnetic metal / insulator / semiconductor heterostructure can be used as effective spin filter.

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INTRODUCTION

The active manipulation of spin-dependent electron transport is the principal task in spintronics [1–3]. One of the effective way to achieve spin polarization of electrons injected into semiconductors is spin-dependent tunnelling through a barrier in ferromagnetic metal / insulator / semiconductor heterostructures [4–11]. The maximum of the spin injection efficiency reaches 52% at 100 K and 32% at 290 K for a MgO barrier on GaAs [5]. High electrical injection of spin-polarized electrons from a Fe film through an Al_2O_3 tunnel barrier into Si has been demonstrated in [8]. However, in Si the electron spin polarization was observed at low temperatures – 30% at 5 K, with polarization extending to at least 125 K.

Although important results in the spin injection have been obtained, high values of the spin polarization of injected electrons at room temperature has not been achieved. Therefore, it is crucial to find a new method of the spin polarization that allows us to achieve high spin-injection efficiency. In this paper, we present new method of the electron spin polarization in ferromagnetic metal / insulator / semiconductor heterostructure, which based on spin-dependent backward scattering on exchange-splitted levels in a 2D quantum well (QW) and on the electron capture by this QW. The QW is formed in the semiconductor near the insulator / semiconductor interface. The insulator layer is thin in order to provide electron tunneling from the ferromagnetic metal and to split levels in the QW by the exchange interaction. For the case, when one of exchange-splitted levels lies in the top region of the QW, the backscattering process of injected electrons becomes dependent on their spins. The capture of backscattered spin-polarized electrons

by the QW leads to an additional Coulomb repulsion for electrons tunneling from the ferromagnetic metal and to a considerable spin-polarized decrease of the current flowing in the heterostructure. In this way, high values of the spin polarization and manipulation of injected electron spins by the charge of the QW can be achieved.

By analogy with the spin polarization in ferromagnetic metal / insulator / semiconductor heterostructures, spin polarization of electron current can be observed in heterostructures consisted of semiconductor substrates and granular films with ferromagnetic metal nanoparticles in an insulator matrix. Ones of these heterostructures are $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructures, where the $\text{SiO}_2(\text{Co})$ is the granular SiO_2 film with Co nanoparticles [12–15]. The 2D QW (accumulation electron layer) with exchange-splitted levels is formed at the interface in the GaAs [14–16]. In $\text{SiO}_2(\text{Co})/\text{GaAs}$ heterostructures extremely large magnetoresistance and the current reduction on the temperature dependence are observed at room temperature.

The paper is organized as follows. In the next section, we study the electron backscattering process on exchange-splitted levels in 2D QW. In Sec. III we consider the capture of backscattered electrons by the QW and the current reduction caused by the QW charging. The spin polarization of electron current caused by the backscattering process and, consequently, by the current reduction is described in Sec. IV. Finally, we summarize the results in Sec. V.

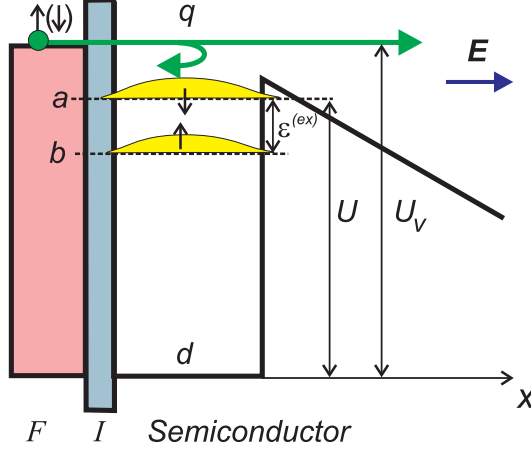


FIG. 1: Backward scattering of injected electron on exchange-splitted levels in the quantum well with the width d . F is the ferromagnetic metal, I is the insulator layer, E is the applied electric field.

INFLUENCE OF LOCALIZED LEVELS IN THE QUANTUM WELL ON THE ELECTRON BACKSCATTERING PROCESS

Let us consider the backward scattering of injected electrons on exchange-splitted levels of the QW in a ferromagnetic metal / insulator / semiconductor heterostructure (Fig. 1). Exchange interaction between electrons in the ferromagnetic metal and electrons in the QW through the thin insulator layer splits electron levels in the QW. Electrons on exchange-splitted sublevels (sublevels a and b in Fig. 1) have opposite spin orientations. Difference of their energies is equal to the exchange energy $\varepsilon^{(ex)}$. For clarification of the main features of scattering dependencies we restrict our consideration on the backscattering process on one of exchange-splitted levels – the top sublevel a with certain spin orientation and neglect insignificant parts of the electron wavefunction on the sublevel a outside the QW.

The electron wavefunction on the sublevel a is the product of the spatial function $u(x)$ and the spin function $\chi_u(\sigma_u)$

$$\psi(x, \sigma_u) = u(x)\chi_u(\sigma_u),$$

where $\sigma_u = \uparrow, \downarrow$ is the electron spin. In the WKB (Wentzel-Kramers-Brillouin) approximation [17] the spatial function in the QW can be written as

$$u(x) = \frac{C_u}{\sqrt{|k_a|}} \sin(k_a x + \pi/4), \quad (1)$$

where $k_a = \sqrt{2mU}/\hbar = \pi(n + 1/2)/d$ is the wavevector of the electron on the sublevel a in the zero ap-

proximation with respect to $\varepsilon^{(ex)}/U \ll 1$, m is the electron mass, U is the energy counted from the QW bottom, d is the width of the QW, C_u is the normalization coefficient, $n = 0, 1, 2, \dots$ is the number of the sublevel a .

The wavefunction of injected electron flying over the QW has the form of the product of the spatial function $v(x)$ and the spin function $\chi_v(\sigma_v)$

$$\varphi(x, \sigma_v) = v(x)\chi_v(\sigma_v),$$

where

$$v(x) = \frac{C_v}{\sqrt{|q|}} \exp(iqx), \quad (2)$$

$q = \sqrt{2mU_v}/\hbar$, U_v is the energy counted from the QW bottom, C_v is the normalization coefficient.

For the interaction $W(x)$ between the injected electron and the electron localized on the sublevel a , in the first approximation with respect to $W(x)$ the probability of the backscattering per unit time is [17]

$$P = \frac{2\pi}{\hbar} |\langle \Phi_f | W | \Phi_{in} \rangle|^2 \eta(U_f), \quad (3)$$

where $\eta(U_f)$ is the density of final states at the energy U_f , $\langle \Phi_f |$ is the final wavefunction and $|\Phi_{in}\rangle$ is the initial wavefunction combined of injected and localized electrons.

If electrons form the singlet spin configuration ($\sigma_u = \uparrow, \sigma_v = \downarrow$ or $\sigma_u = \downarrow, \sigma_v = \uparrow$), then spatial parts of wavefunctions have the symmetric combination

$$\Phi_{in}(x_1, x_2) = u(x_1)v(x_2) + u(x_2)v(x_1),$$

$$\Phi_f(x_1, x_2) = u(x_1)\bar{v}(x_2) + u(x_2)\bar{v}(x_1),$$

where $\bar{v}(x)$ is the wavefunction of the backscattered electron described by Eq. (2) with the substitution $q \rightarrow -q$. For the singlet spin state the backscattering probability (3) is equal to

$$P_S = \frac{8\pi\eta(U_f)}{\hbar} |A + B|^2, \quad (4)$$

where

$$A = \int_0^d u^*(x_1)\bar{v}^*(x_2)W(x_1 - x_2)u(x_1)v(x_2) dx_1 dx_2,$$

$$B = \int_0^d u^*(x_2)\bar{v}^*(x_1)W(x_1 - x_2)u(x_1)v(x_2) dx_1 dx_2,$$

If electrons form the triplet spin configuration ($\sigma_u = \uparrow, \sigma_v = \uparrow$ or $\sigma_u = \downarrow, \sigma_v = \downarrow$), then spatial parts of wavefunctions are antisymmetric

$$\Phi_{in}(x_1, x_2) = u(x_1)v(x_2) - u(x_2)v(x_1),$$

$$\Phi_f(x_1, x_2) = u(x_1)\bar{v}(x_2) - u(x_2)\bar{v}(x_1).$$

For the triplet state the probability (3) can be written as

$$P_T = \frac{8\pi\eta(U_f)}{\hbar} |A - B|^2. \quad (5)$$

Magnitudes A and B in relations (4) and (5) are functions of wavevectors q and k_a . Besides, the wavevector k_a depends on the number n of localized level: $k_a d = \pi(n + 1/2)$. Taking into account wavefunction forms (1) and (2), for the uniform interaction $W(x) = W$ we obtain

$$A = \frac{C_u^2 C_v^2 W (k_a d + 1)}{4i k_a^2 q^2} [\exp(2iqd) - 1]$$

$$B = \frac{C_u^2 C_v^2 W}{2k_a q (k_a^2 - q^2)^2} [(-1)^n \exp(iqd)(iq + k_a) - (iq - k_a)]^2.$$

Probabilities P_S (4) and P_T (5) strongly depend on the difference of wavevectors $\Delta q = q - k_a$ and, consequently, on the difference ΔU between the energy of injected electron $U_v = U + \Delta U$ and the energy of localized electron U in the QW. For $\Delta U \ll U$ the energy difference is

$$\Delta U = \hbar \Delta q \cdot \sqrt{\frac{2U}{m}} = \frac{\hbar^2 k_a \Delta q}{m}. \quad (6)$$

Singlet and triplet backscattering probabilities versus the normalized wavevector difference $\Delta q d$ for $n = 0, 1$ are shown in Fig. 2. Probabilities are normalized by the magnitude of the singlet probability $P_S^{(0)}$ with $n = 0$ and $q = k_a$. In accordance with relation (6), the singlet and triplet probabilities 1S and 1T ($n = 0$) are shown as functions of the variable ΔU (upper axis). In this case the QW contains only one exchange-splitted level. Calculations have been done for $d = 1$ nm and $U = 94$ meV. It is necessary to notice that the probability of the singlet backscattering P_S (curves 1S, 2S) is higher than the triplet backscattering probability P_T (curves 1T, 2T) – the backward scattering becomes dependent on spins of injected electrons. For

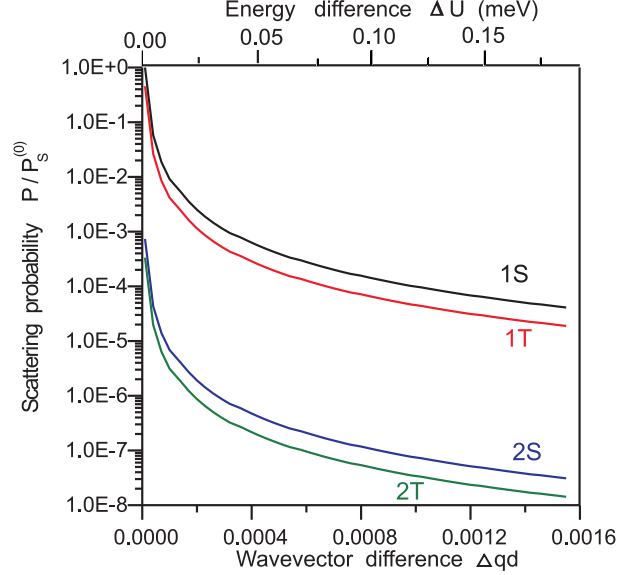


FIG. 2: Probabilities of singlet and triplet backscattering of injected electron with the wavevector q on the QW versus the normalized wavevector difference $\Delta q d = (q - k_a)d$. $k_a = \pi(n + 1/2)/d$ is the wavevector of localized electron, n is the number of level. Probabilities are normalized by the magnitude of the singlet probability $P_S^{(0)}$ with $n = 0$ and $q = k_a$. 1S, 1T are singlet and triplet backscattering on the first level ($n = 0$); 2S, 2T are singlet and triplet backscattering on the second level ($n = 1$), respectively. For the QW with the width $d = 1$ nm and the energy depth $U = 94$ meV the singlet and triplet probabilities 1S and 1T are shown as functions of the difference ΔU between the energy of injected and localized electrons (upper axis).

scattering of injected electrons on the level with $n = 0$ and with the wavevector $q \rightarrow k_a = \pi/2d$, the ratio of singlet and triplet probabilities leads to the relation

$$\frac{P_S}{P_T} \rightarrow \left(\frac{\pi + 3}{\pi + 1} \right)^2 = 2.20.$$

The backscattering probability strongly reduces with growth of Δq and ΔU . The greatest magnitude of backscattering is achieved for the level with $n = 0$. Thus, the backscattering process becomes important, if (1) the QW contains only exchange-splitted level with $n = 0$, (2) one sublevel of the exchange-splitted level with certain spin orientation lies at the top of the QW and (3) the energy of injected electrons is closed to the energy of localized electron on this sublevel.

REDUCTION OF THE CURRENT

The capture of backscattered electrons by the QW leads to the considerable current reduction dependent on spin orientation of injected electrons. If the Fermi

level lies below localized electron levels in the QW, then at a finite temperature these levels are partially filled by electrons. Backscattered electrons are captured by the QW and, in accordance with their spin orientation, they occupy different localized levels. We suppose that the spin relaxation time is greater than the storage time of additional electrons in the QW. Then, for the singlet scattering process backscattered electrons occupy the sublevel b with spin orientation opposite to spin orientation of the sublevel a (Fig. 1). The sublevel b lies below the sublevel a . On the contrary, for the triplet case backscattered electrons fall on the sublevel a . The storage time τ of the presence of additional electrons in the QW depends on the electron-hole recombination, on temperature activation processes, and on the electron tunneling into the conduction band. For underlying levels the storage time τ is greater than the storage time of electrons on overlying ones. The additional charge in the QW leads to the electrostatic blockade of injected electrons and to the current reduction. In this way, the current flowing in ferromagnetic metal / semiconductor heterostructure with QW, which contains exchange-splitted levels, is unstable. This current instability is accompanied by the charge accumulation in the QW and by the current reduction depended on spin orientations of injected electrons.

Let us calculate the reduction of the current. For clarity, we consider the current reduction caused by the singlet backscattering. In the triplet case, the consideration is analogous. The current density flowing over the QW is equal to

$$j = en\mu E, \quad (7)$$

where e is the electron charge, μ is the electron mobility, E is the electric field,

$$n = n_0 \exp\left(\frac{-e\varphi}{kT}\right)$$

is the electron concentration over the QW, n_0 is the electron concentration without an electric field, φ is the potential of the field of additional localized electrons in the QW, k is the Boltzmann constant, and T is the temperature. In the singlet backscattering case, the additional charge accumulates on the sublevel b (Fig. 1). The potential φ of the field caused by this additional charge is determined by the equation [18]

$$\frac{d^2\varphi}{dx^2} = \frac{4\pi e}{\varepsilon}(n_b - n_b^{(0)}), \quad (8)$$

where ε is the dielectric permittivity of the semiconductor in the QW region; n_b and $n_b^{(0)}$ are electron concentrations on the sublevel b in the electric field

and without a field, respectively. If the additional concentration of the charge $n_b - n_b^{(0)}$ is uniformly distributed over the QW width, then the solution of Eq. (8) is given by

$$\varphi(x) = \frac{2\pi e}{\varepsilon}(n_b - n_b^{(0)})x^2.$$

Injected electrons must surmount the additional barrier with the energy height

$$e\varphi = \frac{2\pi e^2}{\varepsilon}(n_b - n_b^{(0)})d^2. \quad (9)$$

Taking into account relations (7) and (9), we obtain the current density of electrons incoming on the sublevel b

$$j_b = P_S j = P_S e \mu E n_0 \exp\left[\frac{-2\pi e^2(n_b - n_b^{(0)})d^2}{\varepsilon kT}\right].$$

Release of additional electrons from the sublevel b is determined by the time τ_b and the current density of outgoing electrons can be written as

$$\bar{j}_b = \frac{e(n_b - n_b^{(0)})d}{\tau_b}.$$

For the equilibrium process $j_b = \bar{j}_b$ and

$$P_S \mu E n_0 \exp\left[\frac{-2\pi e^2(n_b - n_b^{(0)})d^2}{\varepsilon kT}\right] = \frac{(n_b - n_b^{(0)})d}{\tau_b}. \quad (10)$$

Relation (10) is the equation in the unknown additional electron concentration $n_b - n_b^{(0)}$. Taking into account relation (7), we find the current reduction caused by the singlet electron backscattering on the QW

$$R_S = \frac{j}{j_R} = \exp\left[\frac{2\pi e^2(n_b - n_b^{(0)})d^2}{\varepsilon kT}\right]. \quad (11)$$

Current reductions R_S versus the applied electric field E for different times τ_b are shown in Fig. 3. Calculations are performed for $P_S = 2 \cdot 10^{-6}$, width of the QW $d = 2$ nm, permittivity $\varepsilon = 1$, $T = 300$ K, $\mu = 8 \cdot 10^3$ cm²/V·s, and $n_0 = 2.5 \cdot 10^{17}$ cm⁻³. From the presented dependencies we can see that backscattering of injected electrons on exchange-splitted levels and accumulation of electrons in the QW leads to considerable reduction of the current depended on its spin orientation.

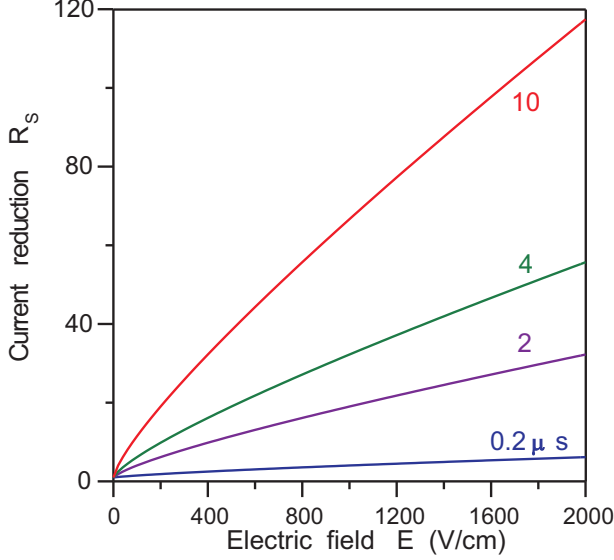


FIG. 3: Current reduction R_S caused by the singlet electron backscattering in ferromagnetic metal / insulator / semiconductor heterostructure with quantum well (QW) contained exchange-splitted levels versus the applied electric field E for different storage time τ_b of additional electrons in the QW. The backscattering probability $P_S = 2 \cdot 10^{-6}$, width of the QW $d = 2$ nm, temperature $T = 300$ K, and the electron concentration over the QW $n_0 = 2.5 \cdot 10^{17} \text{ cm}^{-3}$.

The current reduction depends on the electron concentration n_0 in the semiconductor. For small values of n_0 the additional concentration $n_b - n_b^{(0)}$ in Eq. (10) leads to zero and the reduction is small, $R_S \rightarrow 0$. For great values of the concentration n_0 (for example, close to metal concentrations) the QW contains filled levels and the additional charge in the QW is impossible. As a result of this, there is no any reduction of the current.

For the triplet backscattering case, backscattered electrons accumulate on the level a . The current reduction R_T is determined by relation (11), in which we must perform the substitution $n_b - n_b^{(0)} \rightarrow n_a - n_a^{(0)}$. The additional electron concentration $n_a - n_a^{(0)}$ is the solution of Eq. (10) with substitutions $\tau_b \rightarrow \tau_a$ and $P_S \rightarrow P_T$. In comparison with the singlet case, for $\tau_a \ll \tau_b$ and $P_T < P_S$ the current reduction R_T caused by the triplet backscattering and by the accumulation of electrons in the QW is insignificant.

SPIN POLARIZATION OF ELECTRON CURRENT

The QW with exchange-splitted levels can be regarded as spin filter for injected electrons. Let us consider the spin current flowing over the QW with

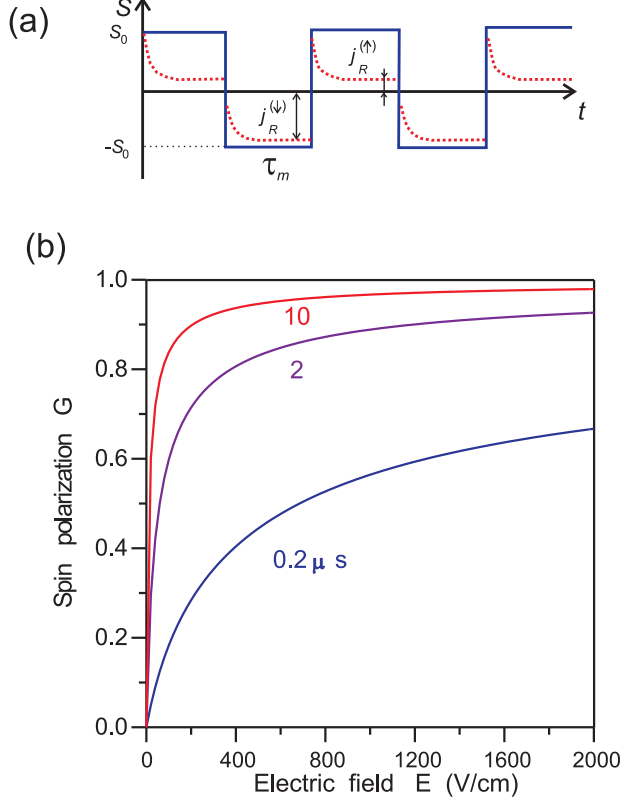


FIG. 4: (a) Current with square modulation of the spin polarization. $j_R^{(\uparrow)}$ and $j_R^{(\downarrow)}$ are currents with spin polarization \uparrow and \downarrow , respectively, after electron backward scattering on the QW. (b) Spin polarization G of the electron current caused by the electron backscattering versus the electric field E for different values of the storage time τ_b .

square modulation of the spin projection $S(t)$ (Fig. 4a)

$$j^{(\alpha)} = S(t)n\mu E, \quad (12)$$

where n is the electron concentration, μ is the mobility, E is the electric field, $\alpha = \uparrow, \downarrow$. We suppose that the modulation period τ_m is much greater than the storage times τ_a and τ_b : $\tau_m \gg \tau_b > \tau_a$. Without spin-dependent backscattering and charge accumulation in the QW the spin current $j^{(\alpha)}$ is not modified. In the presence of singlet and triplet backscattering and accumulation of backscattered electrons in the QW, the spin current $j^{(\alpha)}$ decreases to $j_R^{(\alpha)}$ and the reduction becomes dependent on its spin projection $S(t)$. The magnitude of the reduction of the current $j^{(\uparrow)} \rightarrow j_R^{(\uparrow)}$ caused by the singlet backscattering on the sublevel a (Fig. 1) is higher than the magnitude of the reduction of the current $j^{(\downarrow)} \rightarrow j_R^{(\downarrow)}$ caused by the triplet scattering process. Taking into account relations (7), (11) and (12), for time regions far from pulse edges we can write the spin polarization as

$$G = \frac{|j_R^{(\downarrow)}| - |j_R^{(\uparrow)}|}{|j_R^{(\downarrow)}| + |j_R^{(\uparrow)}|} = \frac{R_S - R_T}{R_S + R_T}.$$

The spin polarization G versus the electric field E has been calculated for different values of the storage time τ_b for backscattering probability $P_S = 2.20 \cdot P_T = 2 \cdot 10^{-6}$, width of the QW $d = 2$ nm, permittivity $\varepsilon = 1$, temperature $T = 300$ K, electron mobility $\mu = 8 \cdot 10^3$ cm²/V·s, concentration $n_0 = 2.5 \cdot 10^{17}$ cm⁻³, and time $\tau_a = 10$ ns (Fig. 4b). One can notice that the spin polarization G increases with growth of the electric field E and the storage time τ_b .

CONCLUSION

The backward scattering of injected electrons on exchange-splitted levels of quantum wells in ferromagnetic metal / insulator / semiconductor heterostructures can be used as the effective way of the spin polarization of the current. The necessary condition to obtain high values of the spin polarization is: one of the exchange-splitted levels must be in the top region of the QW. If the energy of injected electrons is close to the energy of localized electrons, the backward scattering becomes dependent on spins of injected electrons – on singlet or triplet spin configurations. It is found that the probability of the singlet backscattering P_S is higher than the triplet backscattering probability P_T . The capture of backscattered electrons by the QW leads to an additional Coulomb repulsion for electrons and to the considerable spin-dependent reduction of the current flowing in the heterostructure. The spin polarization G of the current increases with growth of the applied electric field and the storage time of electrons in the QW and its high values can be achieved at room temperature. In this way, the QW with exchange-splitted levels in ferromagnetic metal / insulator / semiconductor heterostructures can be regarded as spin filter.

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- [1] S.A. Wolf, D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S. von Molnar, M.L. Roukes, A.Y. Chtchelkanova and D.M. Treger, *Science* **294**, 1488 (2001).
- [2] G. Schmidt, *J. Phys. D: Appl. Phys.* **38**, R107 (2005).
- [3] I. Žutić, J. Fabian, and S. Das Sarma, *Rev. Mod. Phys.* **76**, 323 (2004).
- [4] P.R. Hammar and M. Johnson, *Appl. Phys. Letters* **79**, 2591 (2001).
- [5] X. Jiang, R. Wang, R.M. Shelby, R.M. Macfarlane, S.R. Bank, J.S. Harris, and S.S.P. Parkin, *Phys. Rev. Letters* **94**, 056601 (2005).
- [6] C.H. Li, G. Kioseoglou, O.M.J. van 't Erve, M.E. Ware, D. Gammon, R.M. Stroud, and B.T. Jonker, *Appl. Phys. Letters* **86**, 132503 (2005).
- [7] X.Y. Dong, C. Adelmann, J.Q. Xie, C.J. Palmström, X. Lou, J. Strand, P.A. Crowell, J.-P. Barnes, and A.K. Petford-Long, *Appl. Phys. Letters* **86**, 102107 (2005).
- [8] B.T. Jonker, G. Kioseoglou, A.T. Hanbicki, C.H. Li, and P.E. Thompson, *Nature Physics* **3**, 542 (2007).
- [9] C.H. Li, G. Kioseoglou, O.M.J. van 't Erve, P.E. Thompson, and B.T. Jonker, *Appl. Phys. Letters* **95**, 172102 (2009).
- [10] G. Kioseoglou, A.T. Hanbicki, R. Goswami, O.M.J. van 't Erve, C.H. Li, G. Spanos, P.E. Thompson, and B.T. Jonker, *Appl. Phys. Letters* **94**, 122106 (2009).
- [11] H. Saito, J.C. Le Breton, V. Zayets, Y. Mineno, S. Yuasa, and K. Ando, *Appl. Phys. Letters* **96**, 012501 (2010).
- [12] L.V. Lutsev, A.I. Stognij, and N.N. Novitskii, *JETP Letters* **81**, 514 (2005).
- [13] L.V. Lutsev, A.I. Stognij, N.N. Novitskii, and A.A. Stashkevich, *J. Magn. Magn. Mater.* **300**, e12 (2006).
- [14] L.V. Lutsev, A.I. Stognij, and N.N. Novitskii, *Phys. Rev. B* **80**, 184423 (2009).
- [15] L. Lutsev, *Giant Injection Magnetoresistance. Experimental and Theoretical Study, Perspectives of Applications*. (Lambert Academic Publishing, Saarbrücken, Germany, 2013), ISBN 978-3-659-43964-3 [in Russian].
- [16] L.V. Lutsev, *J. Phys.: Condens. Matter* **18**, 5881 (2006).
- [17] A.S. Davydov, *Quantum Mechanics* (Pergamon Press, Oxford, 1976).
- [18] L.D. Landau and E.M. Lifshitz, *The Classical Theory of Fields*. Vol. 2 (4th ed.) (Butterworth-Heinemann, 1975).